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(6) THE EQUILIBRIUM TEMPERATURE PROBE,

A DEVICE FOR MEASURING TEMPERATURES IN HYPERSONIC BOUNDARY LAYERS,

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THE EQUILIBRIUM TEMPERATURE PROBE, A DEVICE FOR MEASURING TEMPERATURES IN HYPERSONIC BOUNDARY LAYERS

~~by~~

(10) by James E. Danberg

ABSTRACT: The equilibrium temperature probe is a device which may be used to determine the flow temperature in a hypersonic boundary layer. It consists of a sharp, small angled cone of low emissivity metal supported by a thermal insulator. A thermocouple is installed to measure the cone temperature. The cone is held with its axis parallel to the flow. Ideally, the indicated temperature is the adiabatic wall temperature, a property of the flow which when combined with other more easily obtained properties and established relationships provides sufficient information to determine the total temperature of the flow.

The equilibrium temperature probe can be made very small without excessive conduction and radiation effects. This is the main advantage obtained from using the equilibrium temperature probe over the conventional total-temperature probe. In addition, the conical configuration minimizes the probe's interference with the flow.

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

This report describes and analyzes the equilibrium temperature probe, an instrument for measuring flow temperatures at hypersonic speeds. The probe is designed for measuring temperatures within the boundary layer for the high temperature and low density conditions associated with hypersonic wind tunnels.

The work was performed in connection with an experimental program for measuring the characteristics of the hypersonic turbulent boundary layer. This project was sponsored by the Bureau of Naval Weapons under Task No. RMGA-42-034/212-1/F009-10-001.

The author wishes to express his indebtedness to Dr. E. M. Winkler for many helpful discussions during this work and to Mr. E. Petzold for his skill in making the instrument.

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Captain, USN
Commander

K R Enkenhus

K. R. ENKENHUS
By direction

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ILLUSTRATIONS

SYMBOLS

C_p = pressure coefficient = $\frac{p-p_1}{\frac{1}{2}\rho_1 u_1^2}$

c_p = specific heat of constant pressure

h = heat-transfer coefficient

K_1, K_2 = constants (see equation (3))

k = thermal conductivity

M = Mach number

p = pressure

Pr = Prandtl number = $\frac{c_p \mu}{k}$

R = recovery factor

Re_x = Reynolds number based on distance from the leading edge

St = Stanton number = $h/C_p \rho u$

T = temperature

u = velocity

x_c = distance from the cone tip

Y = distance from the wall

β = Mach number factor

γ = ratio of specific heats

μ = viscosity

ρ = density

SYMBOLS (cont'd)

Subscripts

a = primary sensing element

b = support sensing element

e = adiabatic wall conditions

f = calibration conditions

i = incompressible flow conditions

o = supply conditions

p = flat-plate conditions

s = surrounding wall conditions

w = wall conditions

∞ = free-stream conditions

1 = conditions ahead of the cone-probe shock wave

THE EQUILIBRIUM TEMPERATURE PROBE, A DEVICE FOR MEASURING TEMPERATURES IN HYPERSONIC BOUNDARY LAYERS

INTRODUCTION

Normally the experimental study of hypersonic wind-tunnel boundary layers requires either the direct or indirect measurement of the temperature distribution. Of primary interest is the static temperature; however, this quantity cannot be measured directly by any instrument introduced into the flow. This is because the presence of the probe tends to convert the translational energy of the flow in the immediate vicinity of the instrument into thermal energy through shock waves and viscous effects. Thus, probes tend to indicate the total temperature of the flow. Fortunately, this is an adequate measurement because the static temperature is related to the total temperature in a simple way when the Mach number is known.

The conventional total-temperature probe (references (a) through (e)) is the instrument most frequently used for hypersonic boundary-layer work. Such a probe operates by adiabatically compressing a sample of the flow by passing it through a normal shock wave. This sample then enters the probe and passes over a temperature sensing element (e.g., a thermocouple) at relatively low speed. Ideally, the sample is at the total temperature and the sensing element then indicates the total temperature. Practically, in a low density (or low absolute pressure), high-speed and high-temperature flow, the heat losses from the sensing element due to conduction and radiation combined with the small heating potential of the sample cause large deviations in element temperature from the actual total temperature.

As the size of the total-temperature probe is made smaller or the flow density is decreased, the sensing element temperature tends to indicate the external surface temperature of the probe, which is nearly the adiabatic wall temperature associated with the external boundary layer on the probe. This fact suggests that by designing a probe of suitable geometry for which the relationship between adiabatic wall temperature and total temperature is known in terms of the free-stream Mach number, the measurement of the adiabatic wall temperature is sufficient for determining the local total temperature. Such a probe might be called an adiabatic wall temperature probe. Unfortunately some conduction and radiation effects are also present in any practical design and therefore

the sensing element does not indicate adiabatic wall temperature but a temperature associated with the equilibrium between the heat losses and the aerodynamic heating. Therefore, such a probe may be logically called an equilibrium temperature probe. A similar instrument was suggested some years ago by E. R. G. Eckert in what he called a cylinder thermometer (reference (f)), which was designed to measure the adiabatic surface temperature on a cylinder in longitudinal flow.

EQUILIBRIUM TEMPERATURE PROBE DESIGN, THEORY, AND CALIBRATION

Design. A possible configuration for an equilibrium temperature probe might be a sharp, small angled cone made from low emissivity metal and supported by a thermal insulator. One of the main advantages of employing a cone is that the relationship between the flow conditions ahead of the probe to the flow conditions behind the shock wave are known and available over a wide range of Mach numbers. By employing a sharp tip and small cone angle the variation in equilibrium temperature is reduced along the cone and support. In addition such a configuration minimizes the flow interference effects.

Figures 1 and 2 show an experimental model of such a cone probe. The thermocouple (T_a) is soldered directly to the base of the cone, and measures approximately the average temperature of the cone material. Because of the large exposed surface area of the cone and small heat absorbing mass, the tip has a short response time compared with the conventional probe. Polished stainless steel was used in making the probe shown in Figure 1 in order to decrease the emissivity and thereby decrease the transfer of heat by radiation. Subsequent models were improved by reducing the size of all dimensions by one half of those shown in Figure 1. In addition, platinum tips were used with the result that the small radiation effects were further reduced.

The wires from the thermocouple junction are electrically insulated by passing them through separate holes in the ceramic support. This insulator also reduces the conduction of heat from and to the tip. This is particularly important because normally the supporting sting has one or more stagnation regions of high temperature relative to the cone temperature. The major part of the remaining heat conduction is through the thermocouple wires. This can also be reduced by using small diameter wire.

It is important that the cone be oriented with its axis parallel to the flow direction, otherwise it is difficult to account for the effect of angle of attack in the data analysis.

It is also important because the ceramic insulator has very little strength in bending. However, with the probe properly mounted, testing over a wide range of wind-tunnel conditions is possible without damage to the instrument. For example, a probe, one mm in diameter, has been used repeatedly in the NOL Hypersonic Tunnel No. 4 at a Mach number of 6.7 at supply pressures up to 35 atmospheres.

A second thermocouple (T_b) (see Figure 1) has been provided at the sting end of the ceramic insulator to facilitate evaluation of the conduction effects on the tip temperature. That is, the conduction of heat from and to the tip can be calculated approximately from (a) the temperature difference between the tip and the base, (b) a constant obtained from calibration information, and (c) a function of local Mach number derived from theory.

Theory. Ideally the primary thermocouple (T_a) indicates the adiabatic wall temperature (T_e) which is a property of the basic flow, the cone geometry and the type of boundary layer on the cone. Specifically the cone adiabatic wall temperature is directly proportional to the local total temperature, all other conditions being the same.

$$T_o = \left(\frac{T_o}{T_e}\right) T_e \qquad (1)$$

where

$$\left(\frac{T_o}{T_e}\right) = 1/\left[R(1-T/T_o) + T/T_o\right] . \qquad (2)$$

T/T_o is the ratio of static to total temperature in the flow just outside of the cone boundary layer, and R is the temperature recovery factor. Knowing the Mach number of the flow just ahead of the cone tip, and knowing the cone geometry, the ratio T/T_o can be determined from conventional cone tables (reference (g)). Generally the local cone Reynolds number is considerably less than the Reynolds number of transition, and under these conditions the recovery factor equals the square root of the Prandtl number. Because the Prandtl number is only a weak function of temperature, the recovery factor can usually be considered a constant in the wind-tunnel operating range.

As in the conventional probe some radiation and conduction errors are also present in the equilibrium temperature probe. Therefore the indicated cone temperature deviates from the desired adiabatic wall temperature. The heat balance for the cone is the basis for evaluating this temperature error.

$$\underbrace{h(T_e-T_a)}_{\text{Convection}} = \underbrace{-K_1(T_b-T_a)}_{\text{Conduction}} + \underbrace{K_2(T_a^4-T_s^4)}_{\text{Radiation}} \tag{3}$$

Where h = heat-transfer coefficient

K_1 and K_2 are constants

T_s = temperature of the surrounding walls.

By rewriting equation (3), the difference between the measured temperature T_a and the desired adiabatic wall temperature T_e is obtained:

$$T_e-T_a = -(K_1/h)\ (T_b-T_a) + (K_2/h)\ (T_a^4-T_s^4)\quad . \tag{4}$$

The temperature of the surrounding walls, T_s, is assumed to be known, even if only approximately, in all of the following discussions.

Calibration. The unknowns in equation (4) are T_e, K_1/h, and K_2/h. These quantities are not constants but depend on the flow conditions around the probe, i.e., Mach number, pressure, and temperature. Normally, the probe should be calibrated in order to determine the value of K_1/h_f, K_2/h_f, and T_{e_f} under known conditions (subscript f). Three different values of T_a and T_b are required, holding everything else constant, i.e., T_{o_f}, M_f, and T_s. This can be done by applying three different amounts of heating to the sting of the probe. Then K_1/h and K_2/h are calculated for a specific case by multiplying both K_1/h_f and K_2/h_f by the ratio h_f/h, the determination of which will be discussed in the next section. The local value of T_e for the cone can be obtained by inserting the measured and calculated quantities into equation (4), rewritten in the following form:

$$T_e = T_a + \left(\frac{h_f}{h}\right) \left\{ \frac{K_1}{h_f}\ (T_a-T_b) \quad + \quad \frac{K_2}{h_f}\ (T_a^4-T_s^4)\right\}. \tag{5}$$

In order to relate the local value of T_e on the cone to the total temperature in the flow ahead of the cone, equations (1) and (2) are used. The Mach number on the cone that is required to evaluate T/T_o in equation (2) is obtained from the Mach number ahead of the cone, which is presumed to be

known, and from cone tables. The recovery factor may be either calculated from the square root of the Prandtl number or found by using the calibration value of T_{e_f} and the calibration conditions in equations (1) and (2). Since the recovery factor is nearly constant, the calibration value R_f can usually be employed over a wide range of conditions. Comparison of the recovery factor obtained from the calibration conditions with the theoretical value of $Pr^{1/2}$ is usually a check on how well the probe is aligned with the flow.

The variation of h with the basic flow conditions is obtained by assuming the dependence of h on cone Mach number and total temperature based on well established compressible laminar boundary-layer relations. By employing the Mangler transformation for the compressible flow over a cone it is possible to write the local heat-transfer coefficient as (see reference (h))

$$h = .6625 \sqrt{3} \left(\frac{S_t}{S_{t_i}}\right)_p Pr^{1/3} \frac{k}{x_c}\sqrt{\frac{\rho u x_c}{\mu}} \qquad (6)$$

where all the quantities appearing in equation (6) are evaluated just outside the cone boundary layer.

k = thermal conductivity

u = velocity just outside cone boundary layer

x_c = distance from cone tip

μ = coefficient of viscosity

ρ = density just outside cone boundary layer

$(S_t/S_{t_i})p$ is the ratio of the compressible to the incompressible Stanton number on a flat plate, evaluated at a Mach number cor responding to the edge of the cone boundary layer. Since the cone is under conditions of nearly zero heat transfer, the Stanton number ratio can be evaluated at adiabatic conditions. The result is that $(S_t/S_{t_i})p$ can be considered only a function of cone Mach number, and the resulting relation is shown in Figure 3, which is taken from reference (h).

The ratio of the heat-transfer coefficient under any condition to its value at the calibration condition can be written

$$\frac{h}{h_f} = \frac{\left(\frac{S_t}{S_{t_i}}\right)_p}{\left(\frac{S_t}{S_{t_i}}\right)_{p_f}} \left(\frac{Pr}{Pr_f}\right)^{1/3} \sqrt{\frac{k}{k_f} \; \frac{p}{p_f} \left(\frac{T_f}{T}\right)^{1/2} \frac{M}{M_f} \; \frac{\mu_f}{\mu}} \; . \tag{7}$$

Within reasonable limits in temperature and Mach number the following substitutions can be made:

$$\frac{Pr}{Pr_f} = 1 \tag{8}$$

$$\frac{k}{k_f} = \frac{\mu}{\mu_f} = \left(\frac{T}{T_f}\right)^{3/4}$$

where

$$\frac{T}{T_f} = \left(\frac{T}{T_o}\right) \left(\frac{T_o}{T_{of}}\right) \left(\frac{T_{of}}{T_f}\right) \; . \tag{9}$$

The cone pressure p can be related to the static pressure and Mach number in the flow ahead of the cone.

$$\frac{p}{p_1} = 1 + \frac{\gamma M_1{}^2}{2} C_p(M_1) \tag{10}$$

where $C_p(M_1)$ is the pressure coefficient and is a function of cone angle and M_1 as determined from cone tables. Thus equation (7) can be written:

$$\frac{h}{h_f} = \frac{\beta}{\beta_f} \left(\frac{T_o}{T_{of}}\right)^{1/8} \left(\frac{p_1}{p_{1_f}}\right)^{1/2} \tag{11}$$

where

$$\beta = \left(\frac{S_t}{S_{t_i}}\right)_p \left[(p/p_1) \; M \right]^{1/2} (T/T_o)^{1/8} \tag{12}$$

$$\frac{\beta}{\beta_f} = \frac{\left(\frac{S_t}{S_{t_i}}\right)_p}{\left(\frac{S_t}{S_{t_i}}\right)_{p_f}} \left[\frac{(p/p_1)\ M}{(p/p_1)_f\ M_f}\right]^{1/2} \frac{(T/T_o)^{1/8}}{(T/T_o)_f^{1/8}} \ . \qquad (13)$$

For a given cone, β/β_f is just a function of the calibration Mach number, M_f, and the Mach number in front of the cone, M_1, since the cone Mach number M is known in terms of M_1.

In equation (11) $(T_o/T_{o_f})^{1/8}$ contains the temperature, T_o, which is the desired ultimate result of the calculation and hence unknown. However, because of the 1/8 power this term can in most cases be set equal to unity without affecting the result, or at least it is possible to iterate if more accuracy is required. The ratio of the static pressures, p_1/p_{1_f}, must be known. In the case of boundary-layer measurements, however, the assumption of constant static pressure makes p_1/p_{1_f} a constant for a given boundary-layer survey. Since evaluation of the Mach number from Pitot pressure measurements requires the static pressure, this quantity is known in most cases.

For a given cone, β can be calculated and plotted as a function of M_1, the Mach number ahead of the probe over the entire range expected including the calibration condition. Then the value of β/β_f in equation (13) is obtained by finding the appropriate value of β from the graph and forming the ratio β/β_f. Figure 4 shows a graph of β as a function of M_1 for the 5^o half angle cone probe of Figures 1 and 2.

The variation of β with M_1 for a 5^o half angle cone is approximately equal to $M_1^{1/2}$ as can be seen from Figure 4. This becomes more accurate as the Mach number goes to zero because both S_t/S_{t_i} and T/T_o approach one and also, since the cone angle is small, both p/p_1 and M/M_1 approach one as M_1 goes to zero. Therefore equation (13) is equal to $M_1^{1/2}$ with a sufficient degree of accuracy.

A low-speed limitation on the use of the probe is indicated by Figure 4 because as the Mach number of interest approaches zero, β also approaches zero. This is important because the difference between T_e and T_a is inversely proportional to the heat-transfer coefficient and hence to β, with the result that the conduction errors can become large. The useful range can be increased by analyzing in greater detail the subsonic conduction and radiation errors. However, when the probe is used in a hypersonic boundary layer (a) the

size of the probe limits the minimum Mach number encountered; (b) as the probe approaches the surface the difference between probe temperature and the surrounding temperature decreases thereby reducing the radiation heat loss; and (c) the heat losses can be made to have a minimum effect on the tip temperature by better insulation and lower emissivity material.

EXPERIMENTAL RESULTS

Example of Equilibrium Temperature Probe Measurements. Figure 5 shows a typical hypersonic turbulent boundary-layer temperature distribution as obtained with an equilibrium temperature probe. The probe shown in Figures 1 and 2 was used, and in addition the probe was calibrated in the flow just outside the boundary layer so that $p_1/p_{1_f} = 1.0$. The measurements were obtained on a flat plate in the NOL Hypersonic Tunnel No. 4 under the following conditions:

$M_\infty = 6.5$ $\qquad$ $T_w = 300°K$

$P_o = 15.2$ atms $\qquad$ $T_s = 300°K$ (approximate value)

$T_{o_\infty} = 549°K$

The Mach number distribution calculated from Pitot probe data and wall static pressure is shown in Figure 6. The curves marked A and B in Figure 5 are the actual measured temperatures T_a and T_b of the probe. The curve marked C is the calculated total temperature based on the following calibration constants:

$$K_1/h_f = 0.297$$

$$K_2/h_f = 1.1 \times 10^{-10} \ 1/°K^3$$

$$R = 0.826 \quad (Pr_w^{1/2} = 0.8267)$$

The effect of radiation and conduction cancelled to some extent. That is, conduction tended to heat the cone because the support was slightly hotter. However, radiation to the cold wind-tunnel walls tended to reduce the cone temperature.

Near the wall, the total temperature is considerably lower and, hence, the radiation heat loss decreases. The influence on the cone temperature, however, cannot be predicted so easily because although the heat loss due to radiation becomes smaller deep within the boundary layer, on the other hand the local heat-transfer coefficient decreases very rapidly in this region also.

Comparison with the Conventional Total-Temperature Probe. Figure 7 shows the total temperature calculated from the equilibrium probe measurements (curve B) and the measurement from a conventional total-temperature probe (curve A). The total-temperature probe was instrumented to indicate the temperature of the thermocouple wires at the point the wires entered the support. The temperature of thermocouple at the support is shown as curve C. The difference then between curves A and C is an indication of the conduction along the primary thermocouple wires.

When the conventional probe is in the free stream, the external surfaces are subject to a temperature considerably lower than T_o. As a result, some heat from the sensing element flows toward this low temperature region. Because of the low speed of the internal flow, the heat-transfer rate to the sensing element is small, and consequently, small heat losses become a significant fraction of the heat input. Under these conditions the element temperature is considerably lower than T_o. A similar result was obtained by Wood (references (d) and (e)) in the free stream and with a large probe.

The preceding is the case when the entire probe is immersed in a uniform stream as during calibration. However, when probing the boundary layer with a conventional total-temperature probe the situation is quite different because usually the support extends into the free stream exposing its surfaces to free-stream adiabatic wall temperature. The primary element, on the other hand, is exposed to local T_o which near the wall in a high heat-transfer case, can be several hundred degrees Centigrade below T_{of} and hence even below T_e of the free-stream. In this case, heat flows from the relatively hot support to the colder element. Thus, if the ability of the internal flow to absorb this heat is low, the element is considerably higher in temperature than the local T_o. This is shown in Figure 7 in the region less than one mm from wall. Similar errors may result from radiation between the element and the shield as well as from conduction if the shield temperature is approximately the same as that of the support. Thus the error in a conventional total-temperature probe cannot be represented by a recovery factor just dependent on the internal flow conditions because it does not account for changes in heat conduction or radiation due to the changing external flow field. If curve B (Figure 7) is the correct T_o distribution then a recovery factor greater than one is required to transform curve A into B in the region less than one mm from the wall.

An important region in Figure 7 is where curves A and C cross since at that point the conduction losses are zero and the indicated temperature equals the actual local total

temperature. The curves in fact do cross almost on the T_o curve based on equilibrium temperature measurements.

CONCLUSIONS

The equilibrium temperature probe is essentially a sharp, small angled cone made from low emissivity metal and supported by a thermal insulator. A temperature sensing element measures the temperature of the cone which ideally would be the cone adiabatic wall temperature. The adiabatic wall temperature is a property of the flow which when combined with other easily obtained quantities (Mach number and cone geometry) and established relationships (cone flow and laminar recovery factor) provides sufficient information to determine the total temperature of the flow.

The advantages of indirectly measuring the total temperature in a hypersonic boundary layer by an equilibrium temperature probe are:

a. The element area, in this case the cone surface, is large compared to the conduction path, thereby decreasing the required correction to the measurement for conduction.

b. Under some conditions the local heat-transfer coefficient at the sensing element is larger for the cone probe than for the conventional probe because of the higher local flow velocity. This also reduces the conduction error.

c. The cone and its supporting insulator are all at approximately the same temperature, which further decreases the magnitude of conduction losses.

d. Both the radiation and conduction losses can be evaluated with the aid of a calibration procedure. However, radiation effects will limit the usefulness of the instrument at extremely high temperature.

e. The size of the probe is not as restricted by manufacturing difficulties as is the more complicated shielded thermocouple of the conventional total-temperature probe.

f. The small angle cone presents a minimum disturbance to the external flow field and this reduces the reservation concerning the use of probes in close vicinity of a wall.

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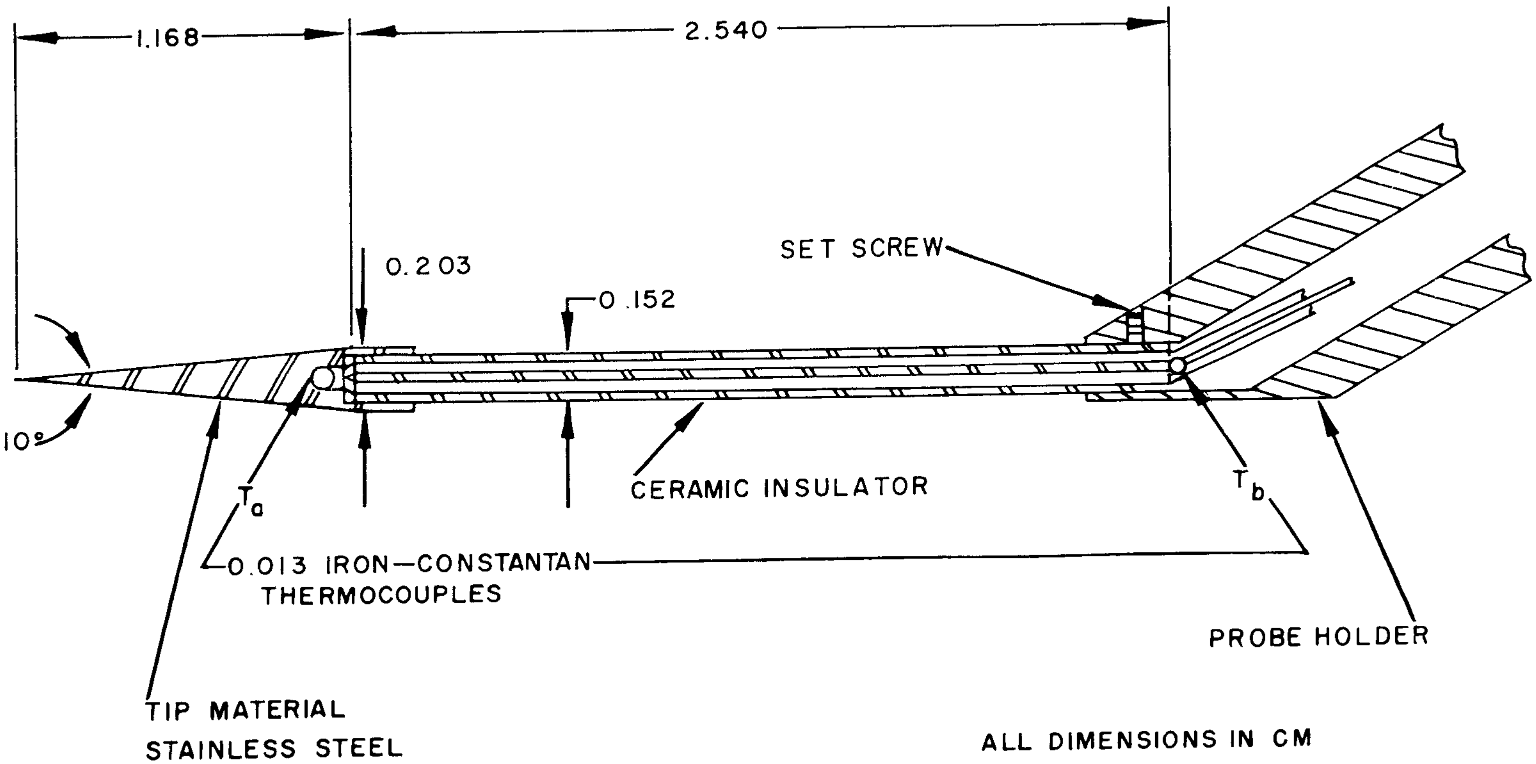

FIG. 1 SKETCH OF EQUILIBRIUM TEMPERATURE PROBE

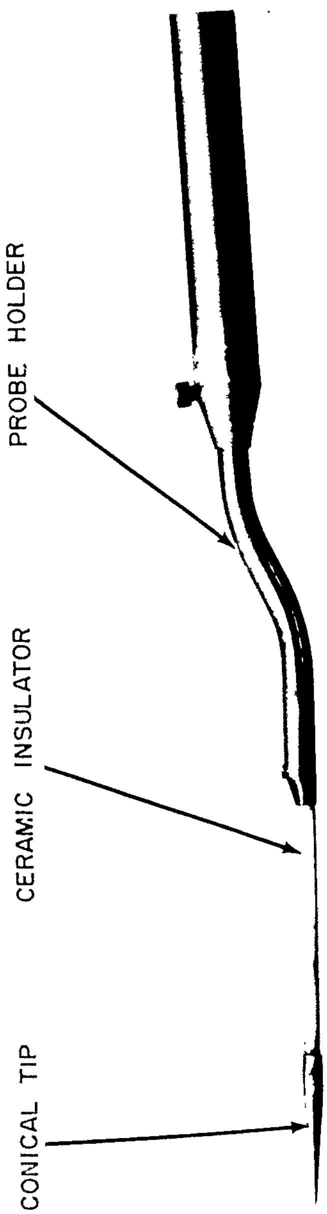

FIG. 2 PHOTOGRAPH OF EQUILIBRIUM TEMPERATURE PROBE

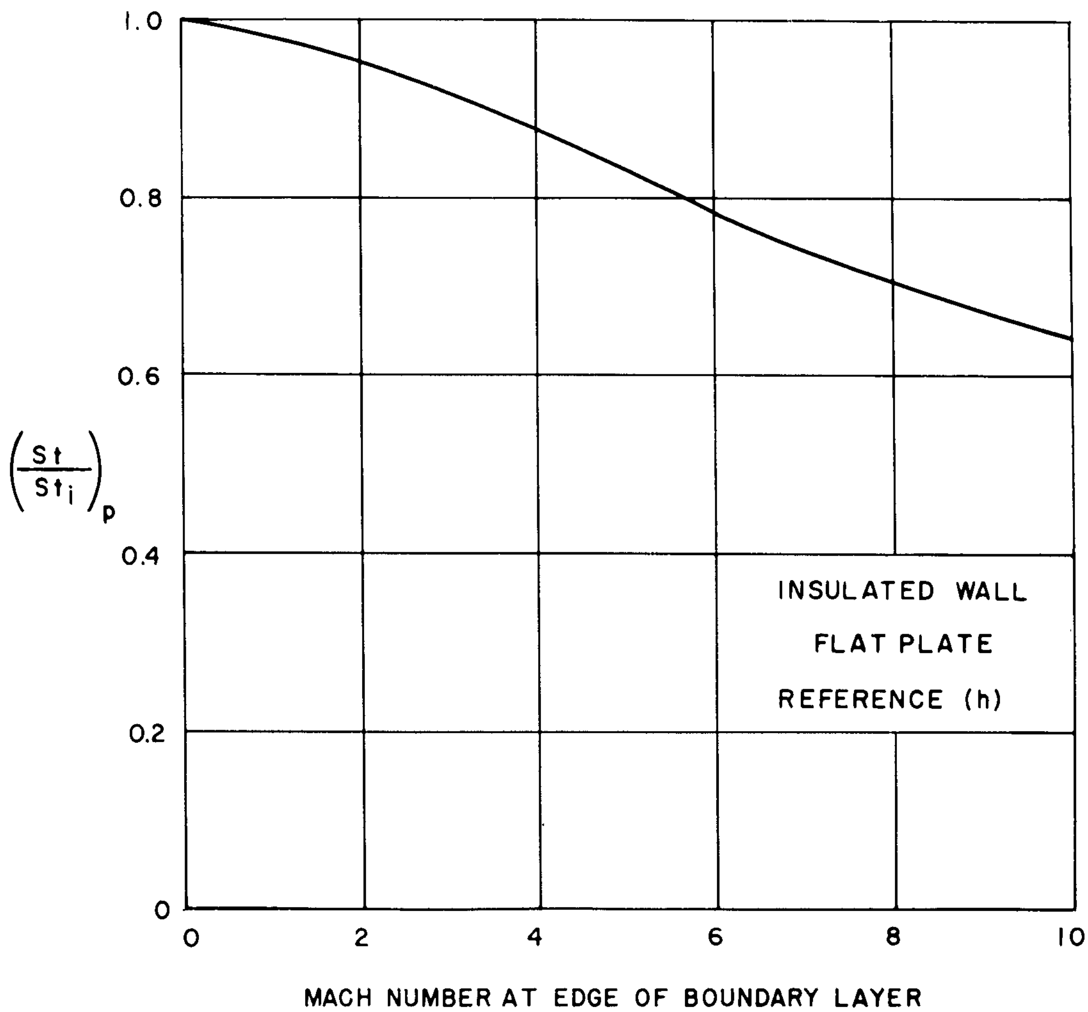

FIG. 3 RATIO OF COMPRESSIBLE TO INCOMPRESSIBLE STANTON NUMBER

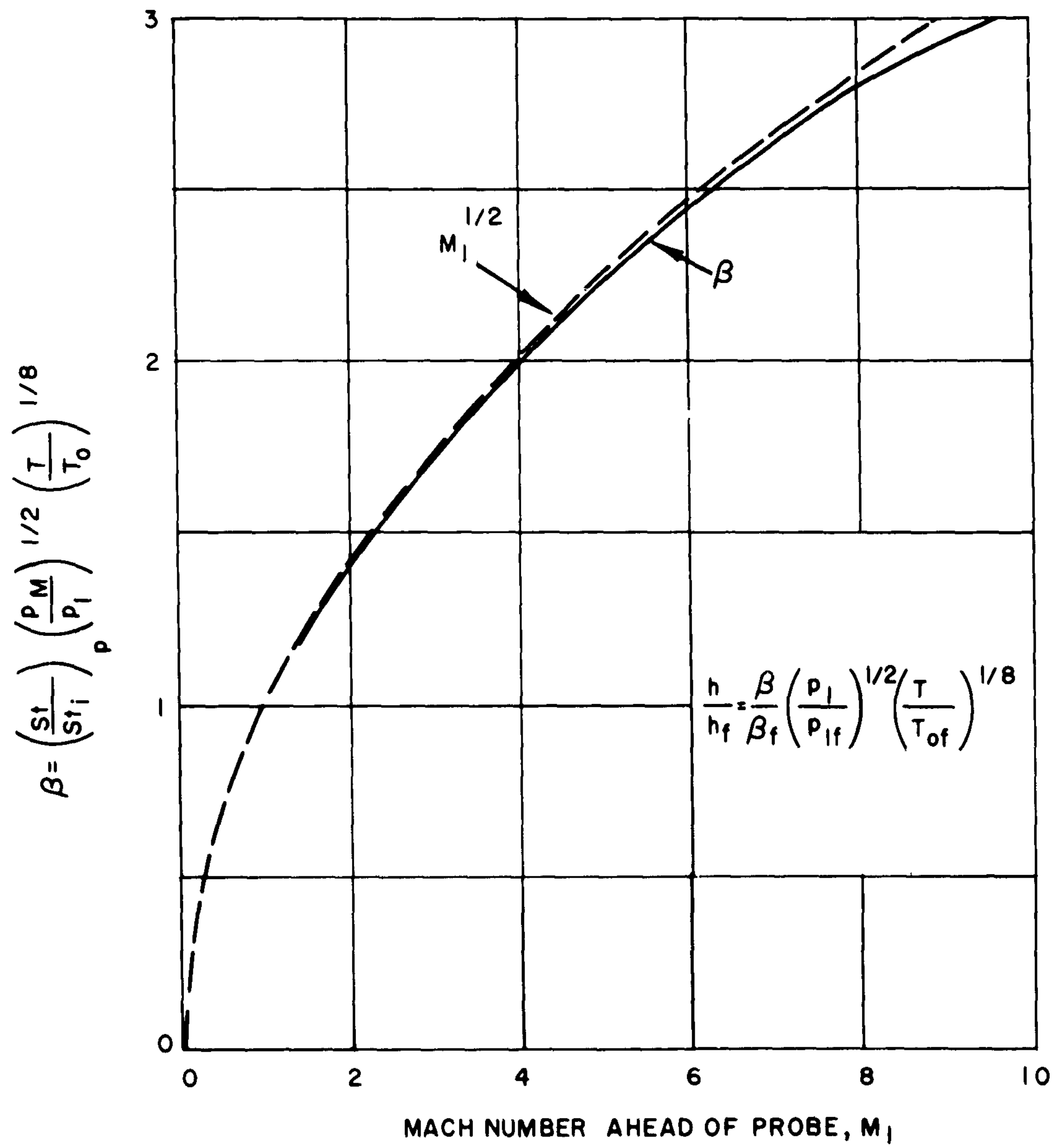

FIG 4 MACH NUMBER DEPENDENT FACTOR IN THE HEAT TRANSFER COEFFICIENT RATIO

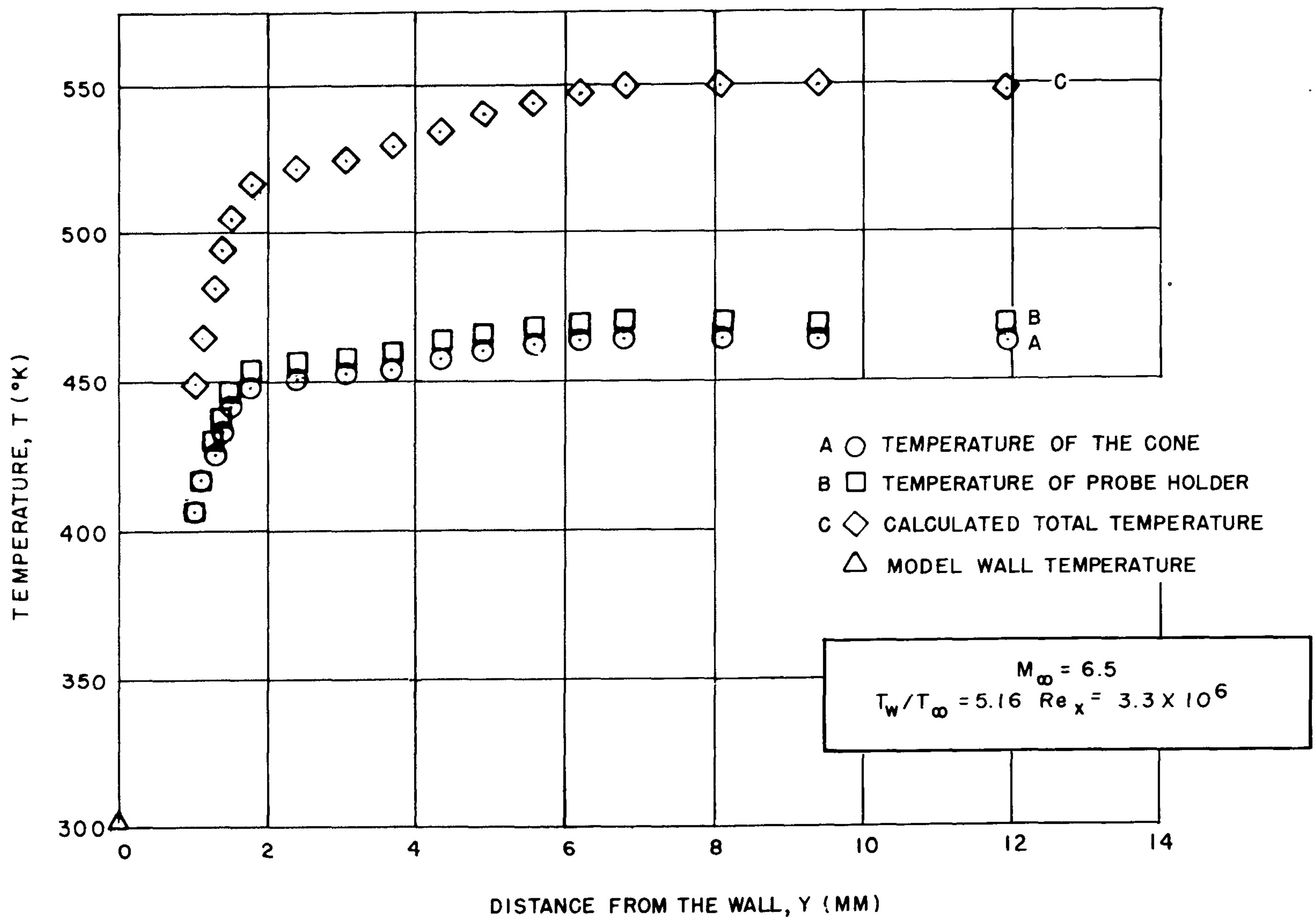

FIG. 5 EQUILIBRIUM PROBE MEASUREMENTS

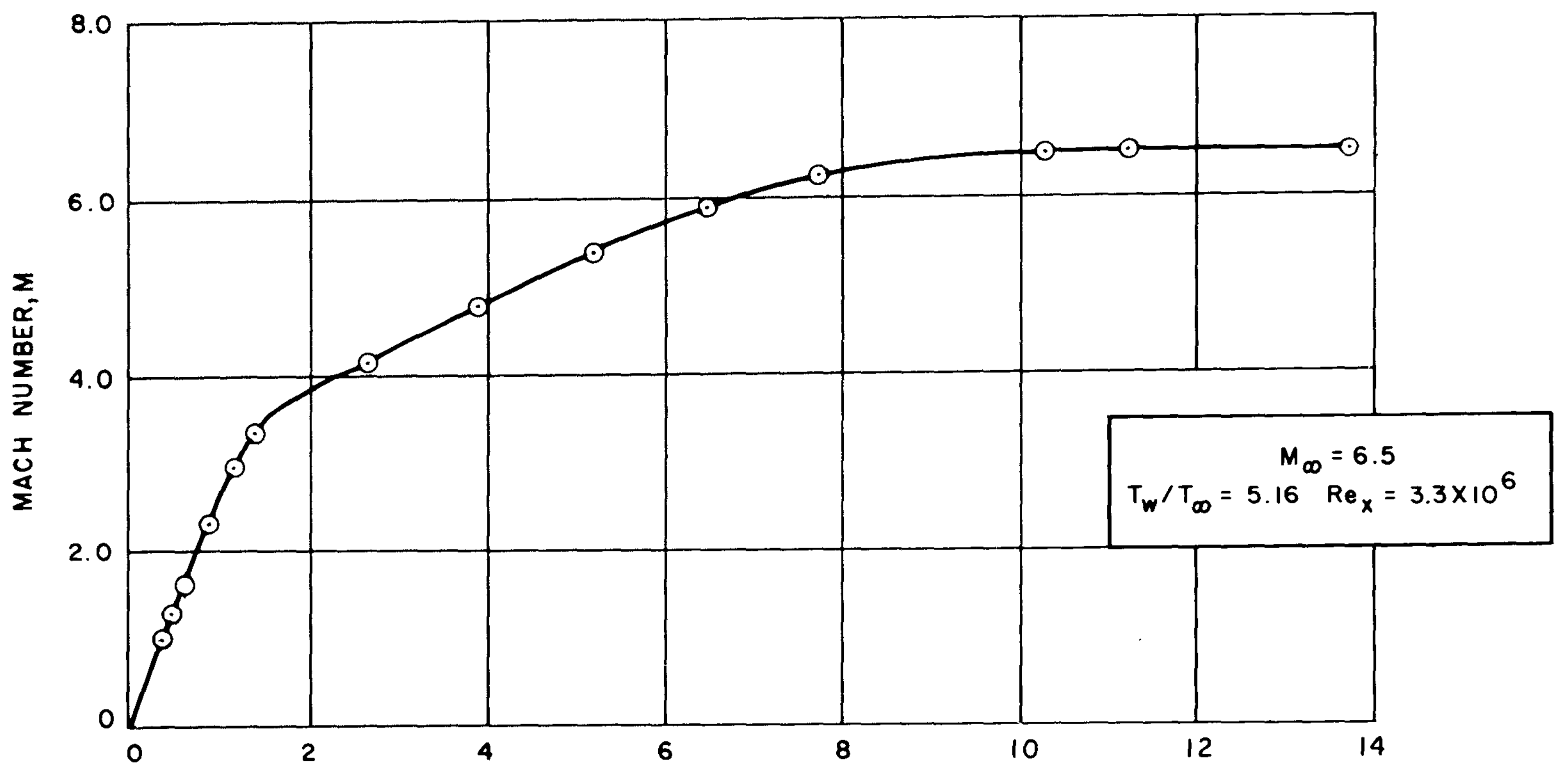

FIG. 6 MACH NUMBER VARIATION IN BOUNDARY LAYER

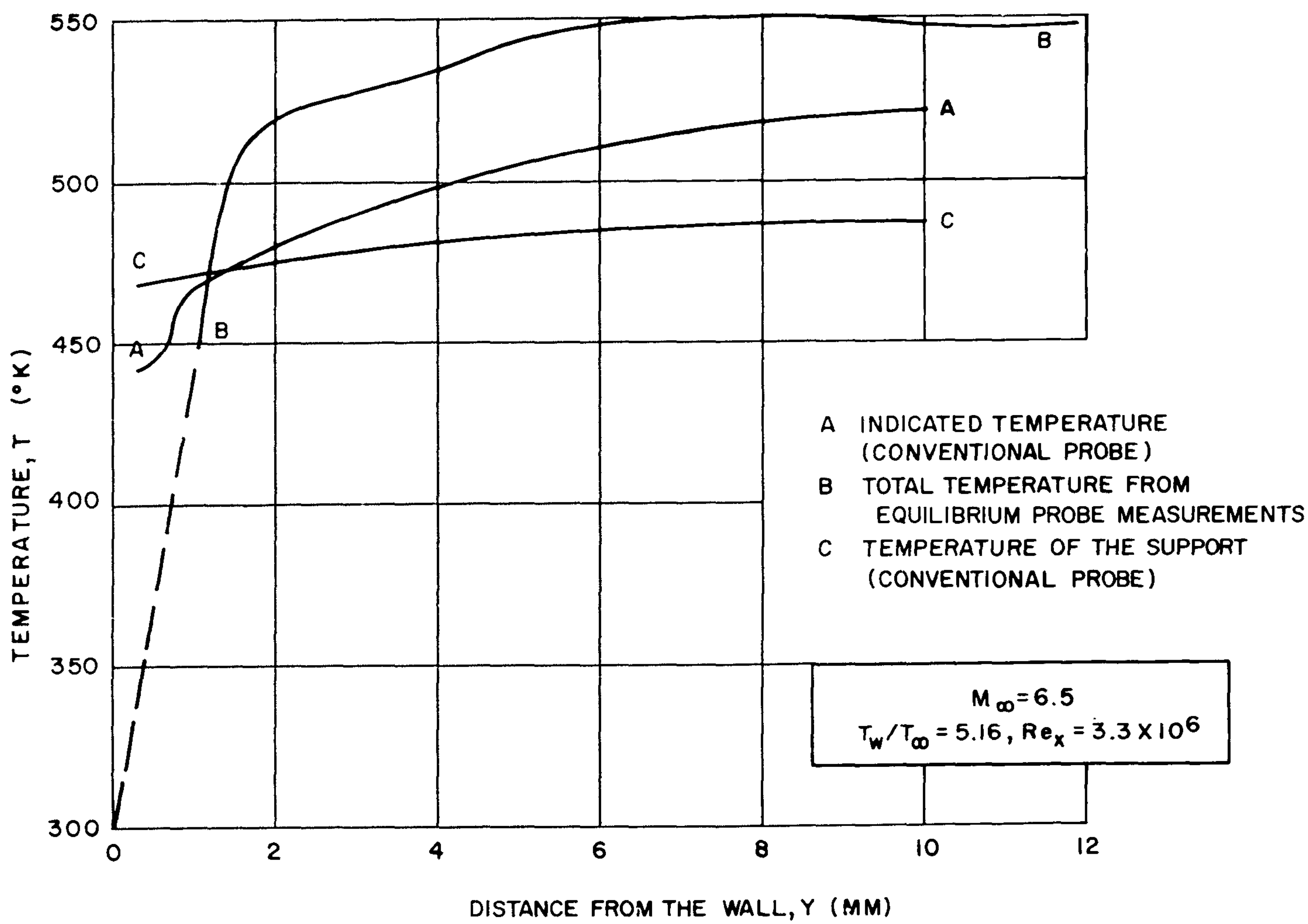

FIG. 7 COMPARISON BETWEEN COVENTIONAL TOTAL TEMPERATURE PROBE MEASUREMENTS AND TOTAL TEMPERATURE

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Equilibrium temperature probe is a device used to determine flow temperature in hypersonic boundary layer. It consists of a sharp, small angled cone of low emissivity metal supported by a thermal insulator. A thermocouple is installed to measure cone temperature. The cone is held with its axis parallel to flow so that ideally, indicated temperature is adiabatic wall temperature, a property of flow which when combined with other more easily obtained properties and established relationships provides sufficient information to determine total temperature of the flow.

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